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# Comparison of MODIS and AERONET derived aerosol optical depth over the Ganga Basin, India

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**Abstract.** The Moderate Resolution Imaging Spectroradiometer (MODIS) onboard EOS Terra measures global aerosol optical depth and optical properties since 2000. MODIS aerosol products are freely available and are being used for numerous studies. In this paper, we present a comparison of aerosol optical depth (AOD) retrieved from MODIS with Aerosol Robotic Network (AERONET) data for the year 2004 over Kanpur, an industrial city lying in the Ganga Basin in the northern part of India. AOD retrieved from MODIS ( $\tau_{aMODIS}$ ) at  $0.55\mu\text{m}$  wavelength has been compared with the AERONET derived AOD ( $\tau_{aAERONET}$ ), within an optimum space-time window. Although the correlation between  $\tau_{aMODIS}$  and  $\tau_{aAERONET}$  during the post-monsoon and winter seasons ( $R^2 \sim 0.71$ ) is almost equal to that during the pre-monsoon and monsoon seasons ( $R^2 \sim 0.72$ ), MODIS is found to overestimate AOD during the pre-monsoon and monsoon period (characterized by severe dust loading) and underestimate during the post-monsoon and winter seasons. The absolute difference between  $\tau_{aMODIS}$  and  $\tau_{aAERONET}$  is found to be low ( $0.12 \pm 0.11$ ) during the non-dust loading season and much higher ( $0.4 \pm 0.2$ ) during dust-loading seasons. The absolute error in  $\tau_{aMODIS}$  is found to be about  $\sim 25\%$  of the absolute values of  $\tau_{aMODIS}$ . Our comparison shows the importance of modifying the existing MODIS algorithm during the dust-loading seasons, especially in the Ganga Basin in northern part of India.

**Keywords.** Atmospheric composition and structure (Pollution-urban and arid region; Aerosols and particles) – Radio science (Remote sensing)

## 1 Introduction

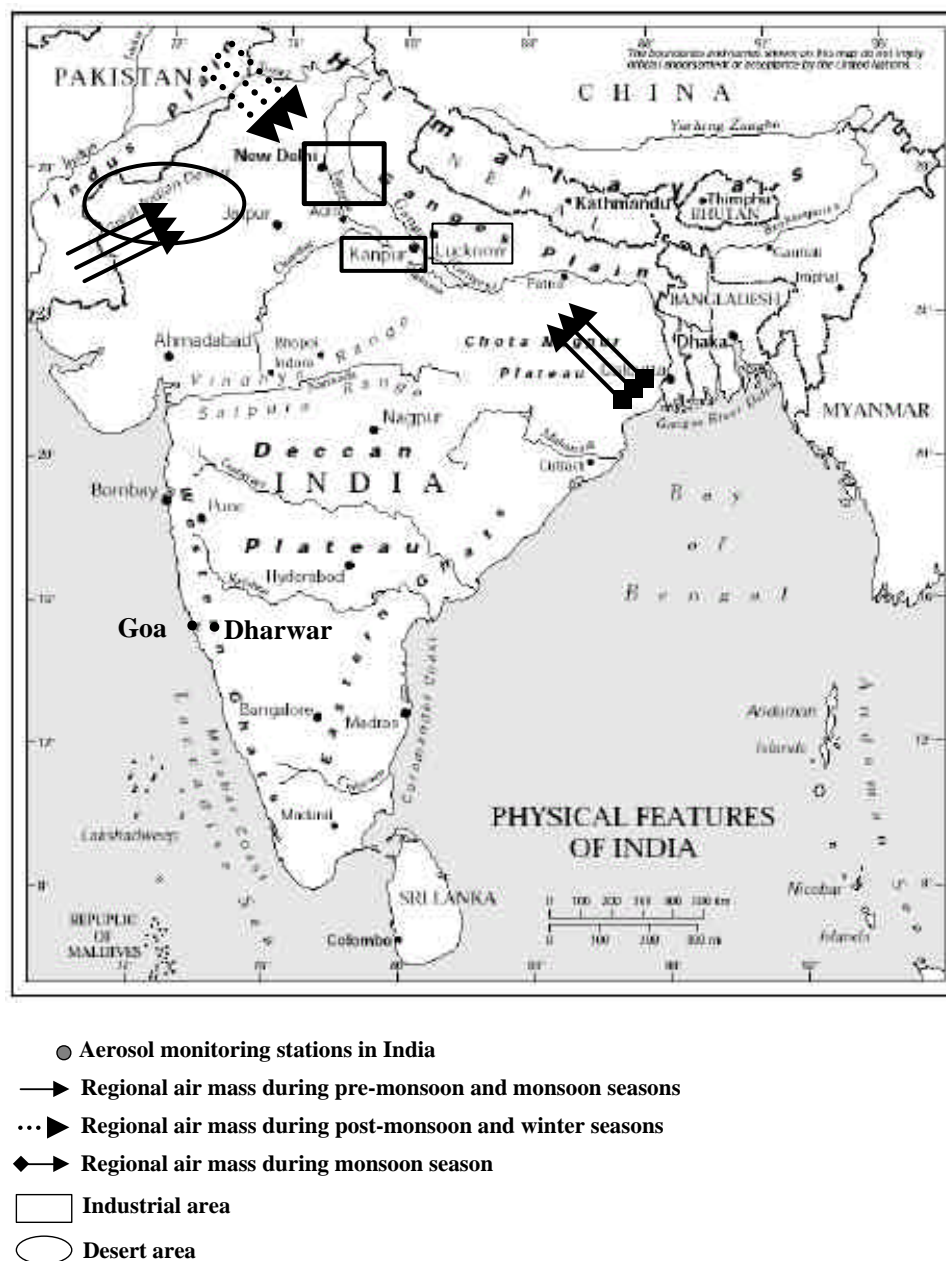
Estimation of the radiative forcing of the aerosol is uncertain due to the incomplete knowledge of the microphysical

and optical properties of aerosols and their extreme heterogeneous spatial distribution (Charlson et al., 1992; Tegen et al., 1996; Hansen et al., 1997; Haywood and Boucher, 2000; Satheesh and Ramanathan, 2000; Boucher and Haywood, 2001). The knowledge of spatial and temporal distributions of aerosols on a global scale is important to understand the dynamics of aerosol and the associated influence on global climatic conditions. Satellite remote sensing is an essential tool for monitoring the global aerosol budget and their radiative effects on climate (Charlson, 1992; Penner et al., 1992; Andreae, 1995; Kaufman et al., 1997a, 2002a). A single ground-based aerosol monitoring station is not very useful in assessing global aerosol distribution due to the strong spatial and temporal variability of aerosol particles in the atmosphere. However, the network of ground-based stations are essential in estimating the microphysical and optical properties of the ambient aerosol column in a particular region (Kaufman et al., 1994; Holben et al., 1996, 1998), which is required to validate the satellite measurements and to increase the accuracy of the retrieval techniques of the satellites in a regional scale. Most of the aerosol properties have been derived over the ocean from remote sensing data because of the minimum spatial variability of the ocean surface reflectance. The first instrument designed for aerosol measurements over land was the Polarization and Directionality of Earth's Reflectance (POLDER), which was only operational for nine months (Boucher and Tanré, 2000; Deuzé et al., 2000). The launch of Earth Probe Total Ozone Measuring Spectrometer (EP-TOMS) in 1996, which can detect absorbing aerosols from the backscattering in the ultraviolet spectra ( $0.34$  and  $0.38\mu\text{m}$ ) both over the land and ocean (Hsu et al., 1996; Herman et al., 1997), added new insight into investigations of elevated dust and smoke layers above the scattering atmosphere.

The launch of MODIS on board the Earth Observing System (EOS) Terra and Aqua satellites (King et al., 1999) provides a unique opportunity in deriving spectral information of aerosol parameters over land in the visible wavelength region. MODIS-derived aerosol properties over land

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**Fig. 1.** Study area with regional air mass during different seasons. The industrial areas near Kanpur are marked by solid boxes and the western Thar Desert is shown by ellipsoid.

(Kaufman et al., 1997b; Chu et al., 1998, 2002; Ichoku et al., 2002) and over the ocean (Tanré et al., 1997; Remer et al., 2002) have been validated by more than 30 Aerosol Robotic Network (AERONET) stations worldwide. Recently, Vinoj et al. (2004) have used MODIS data to study aerosol properties over the Bay of Bengal and compared them with ship-borne measurements. But discrepancies still remain in understanding the aerosol properties in many parts of the world, especially over the Indian sub-continent due to the absence of ground-based aerosol monitoring stations.

Currently, 192 AERONET stations are operational worldwide. In the Indian sub-continent, three stations were

originally deployed at Kanpur (26° N, 80° E), Goa (15° N, 73° E) and Dharwar (15° N, 74° E), out of which only the Kanpur station is still functional (Fig. 1). Besides AERONET, the Indian Space research Organization (ISRO) has established a few ground-based aerosol monitoring stations across the country (Krishna Moorthy et al., 1999), where multi-wavelength radiometers are operational (Fig. 1). But in view of the strong spatial and temporal variability of aerosols, the existing ground-based aerosol-monitoring networks in India are not sufficient to establish an aerosol climatology of the whole country. Therefore, the need for satellite measurements and validation has grown manifold in India,

especially over the Ganga Basin in the northern part of India, where currently only one station (Kanpur) is monitoring aerosols continuously. In this paper, comparison of MODIS-derived aerosol optical depth (AOD,  $\tau_a$ ) with AERONET measurements over Kanpur city has been made for the year 2004 which shows significant differences during dust events in pre-monsoon season.

## 2 Study area

Ganga Basin, one of the largest drainage basins in the world, is bordered by the Himalayas to the north and Vindhyan–Satpura ranges to the south (Fig. 1). The Ganga Basin is traversed by the two main rivers, Ganga and Yamuna, and their tributaries. More than 45 million people live in the Ganga Basin, where, due to urbanization and industrialization, the population burden is continuously increasing; as a result the pollution level is increasing over the region as mapped by ADEOS POLDER 1 data (Goloub et al., 2001). Due to the mixing of aerosols loaded by natural and anthropogenic sources, the aerosol parameters over the Ganga Basin show strong seasonal variability (Singh et al., 2004). The Ganga Basin experiences four seasons annually, winter (December–February), pre-monsoon (March–May), monsoon (June–August) and post-monsoon (September–November). During the post-monsoon and winter seasons, the whole region is dominated by aerosols of anthropogenic sources loaded by local and northerly winds (Singh et al., 2004), whereas during the pre-monsoon and monsoon seasons, dust is the dominant component (Dey et al., 2004). The loading of different types of aerosols over the Ganga Basin in different seasons makes the retrieval of aerosol parameters from satellite measurements more problematic.

## 3 Data

MODIS data are available at different processing levels, level 1.0 (geolocated radiance and brightness temperatures), level 2.0 (retrieved geophysical data products) and level 3.0 (King et al., 2003). AERONET data are also available at three levels, level 1.0 (unscreened), level 1.5 (cloud-screened) and level 2.0 (quality assured) (Holben et al., 1998). In the present study, level 2.0 MODIS data have been used to retrieve AOD and compared with level 2.0 AOD data of AERONET during January–November 2004. Level 2.0 AERONET data for December 2004 has not been released, hence it is excluded from the comparison.

Version 4.2.2 (collection 4) of MOD04\_L2 (data collected from Terra platform) and MYD04\_L2 (data collected from Aqua platform) data products have been used in this study. This new version is released during 2004, where modification has been made in the algorithm to improve the aerosol data product. During the monsoon season, due to the non availability of cloud free MODIS data over the northern part of India, it was not possible to make any comparison for the month of August.

## 3.1 MODIS

The radiant energy reflected and emitted by the Earth carries a signature of the atmospheric properties as it passes through the atmosphere. Satellites sensors can quantify several atmospheric properties by measuring the wavelength, angular and polarization of this reflected and emitted energy (Kaufman et al., 2002a). MODIS has 36 bands ranging from 0.4- to 14.4- $\mu\text{m}$  wavelengths with three different spatial resolutions (250, 500 and 1000 m).

MODIS measures AOD with an estimated error of  $\pm 0.05 \pm 0.20 \tau_a$  over the land (Chu et al., 2002) at 0.47 and 0.66 wavelengths at 550-m resolution and extrapolated to a 0.55- $\mu\text{m}$  wavelength (Ichoku et al., 2002). Except for dust, effect of the aerosols on the radiance measured by satellite decreases with wavelength (Kaufman, 1993), therefore the effect is much smaller in the mid-infrared compared to those of a visible wavelength. The dark pixels have been identified and their surface reflectance has been measured in blue (0.47  $\mu\text{m}$ ) and red (0.6  $\mu\text{m}$ ) channels from the remotely sensed reflectance in the mid-infrared channels (2.1 and 3.8  $\mu\text{m}$ ). Kaufman et al. (1997b) have developed empirical relationships over the vegetated surfaces to deduce surface reflectance ( $\rho_s$ ) at 0.47- and 0.66- $\mu\text{m}$  wavelengths from the observed  $\rho_s$  at 2.1- $\mu\text{m}$  wavelength. MODIS aerosol retrieval over land is limited to pixels of  $\rho_s^{2.1 \mu\text{m}} < 0.2$  to minimize the errors. The aerosol type has been determined from the information on the global aerosol distribution and a suitable aerosol dynamic model has been chosen to invert the measured radiance by satellites to produce aerosol data products. The detailed methodology of the retrieval of AOD has been discussed by Kaufman et al. (1997b).

## 3.2 AERONET (Aerosol RObotic NETwork)

The AERONET (Aerosol RObotic NETwork) program is an inclusive federation of ground-based remote-sensing aerosol networks established by NASA and greatly expanded upon by other agencies, institutes and university partners throughout the world (Holben et al., 1998). The goal of this program is to assess aerosol optical properties and to validate satellite retrievals of aerosol optical properties. The network imposes standardization of instruments, calibration, and processing. Data from this collaboration provides globally distributed observations of spectral aerosol optical depths, inversion products, and precipitable water in geographically diverse aerosol regimes. A CIMEL sun/sky radiometer takes measurements of the direct Sun and diffuse sky radiances at eight spectral channels within the range from 0.34 to 1.02  $\mu\text{m}$ . Sky measurements are performed at 0.44-, 0.67-, 0.87- and 1.02- $\mu\text{m}$  wavelengths through a large range of scattering angles from the Sun, using a constant aerosol profile to retrieve size distribution, phase function, and AOD (Holben et al., 1998). The uncertainty in retrieval of AOD under cloud free conditions is  $< \pm 0.01$  for  $\lambda > 440 \text{ nm}$  and  $< \pm 0.02$  for shorter wavelengths. Under the AERONET program, a CIMEL sun/sky radiometer was deployed on the campus of the Indian Institute of

**Table 1.**  $R^2$  value obtained by linear and 2nd degree interpolation for fourteen points  $\tau_{aAERONET}$  of January 2004.

DAY.TIME	$R^2$ (Linear interpolation)	$R^2$ (2nd degree interpolation)
10.072	0.9307	0.9941
11.085	0.9752	0.9992
12.071	0.9837	0.999
13.075	0.9765	0.9989
15.074	0.9803	0.9994
18.081	0.971	0.9991
27.05	0.9638	0.9989
27.0805	0.9599	0.9991
28.054	0.9601	0.9992
29.0445	0.9518	0.9917
29.0755	0.9539	0.9979
30.053	0.9495	0.9966
30.328	0.948	0.9969
31.074	0.9639	0.9987

Technology (IIT) Kanpur, which is continuously operational since January 2001.

#### 4 Methodology

We generated spatial statistics of the MODIS derived AOD ( $\tau_{aMODIS}$ ) over Kanpur and corresponding statistics from temporal subsets of AERONET derived AOD ( $\tau_{aAERONET}$ ). The means and standard deviations of identical MODIS and AERONET parameters are compared. It would be inappropriate to compare single MODIS pixel values directly to AERONET point measurement for many reasons. Firstly, the parameter value derived from MODIS is the spatial average over the pixel surface, while the value from AERONET is of a point in space. Secondly, the probability of overlap of the center of a pixel and the point observed by the Sun photometer is very low. Another problem is that there is a time difference between the points (in temporal space) of acquisition of data by the two instruments. Air masses are constantly in motion, therefore, an air mass captured by MODIS across a certain horizontal span over a Sun-photometer site, is sampled by the Sun photometer during a certain time period (Ichoku et al., 2002).

To calculate the MODIS value at the AERONET station ( $P_a$ ), we have extracted the parameter value of pixels lying in  $\pm 1/4^\circ$  of  $26.45^\circ$  N latitude and  $80.346^\circ$  E longitude (Kanpur AERONET station) using HDFLook (Gonzalez and Deroo, 2003). A table of AOD along with the corresponding latitude and longitude for these pixels was prepared and the mean ( $\mu$ ) and standard deviation ( $\sigma$ ) have been calculated. From these extracted values, the five nearest values lying within  $\mu \pm \sigma$  have been chosen to reduce the error. A scatter plot of these five points has been drawn having independent variables, latitude and longitude, on the X and Y-axes and

dependent variable AOD on the Z-axis. A multiple regression plane has been fitted to these points of the form:

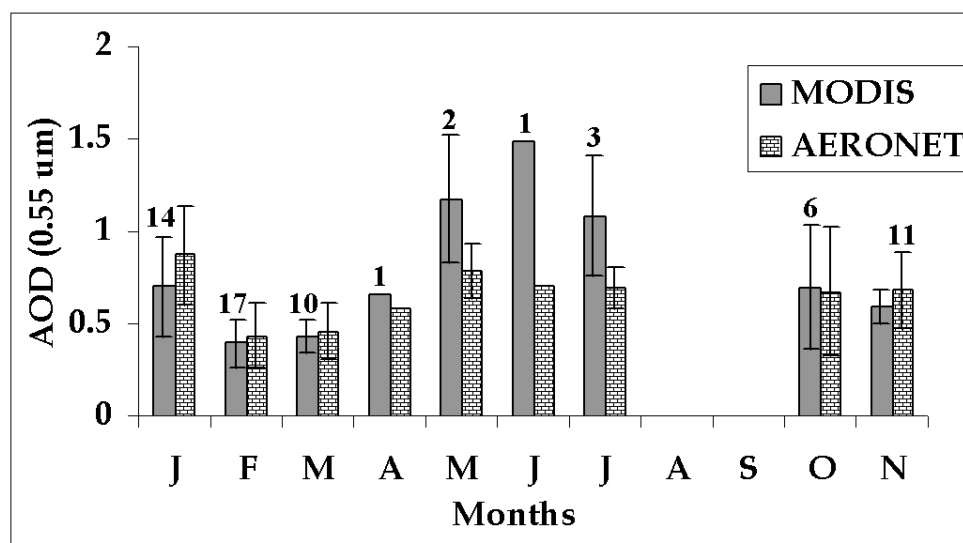
$$Z = aX + bY + c. \quad (1)$$

Using Eq. (1), we have calculated the MODIS derived AOD for the Kanpur AERONET station ( $P_a$ ).

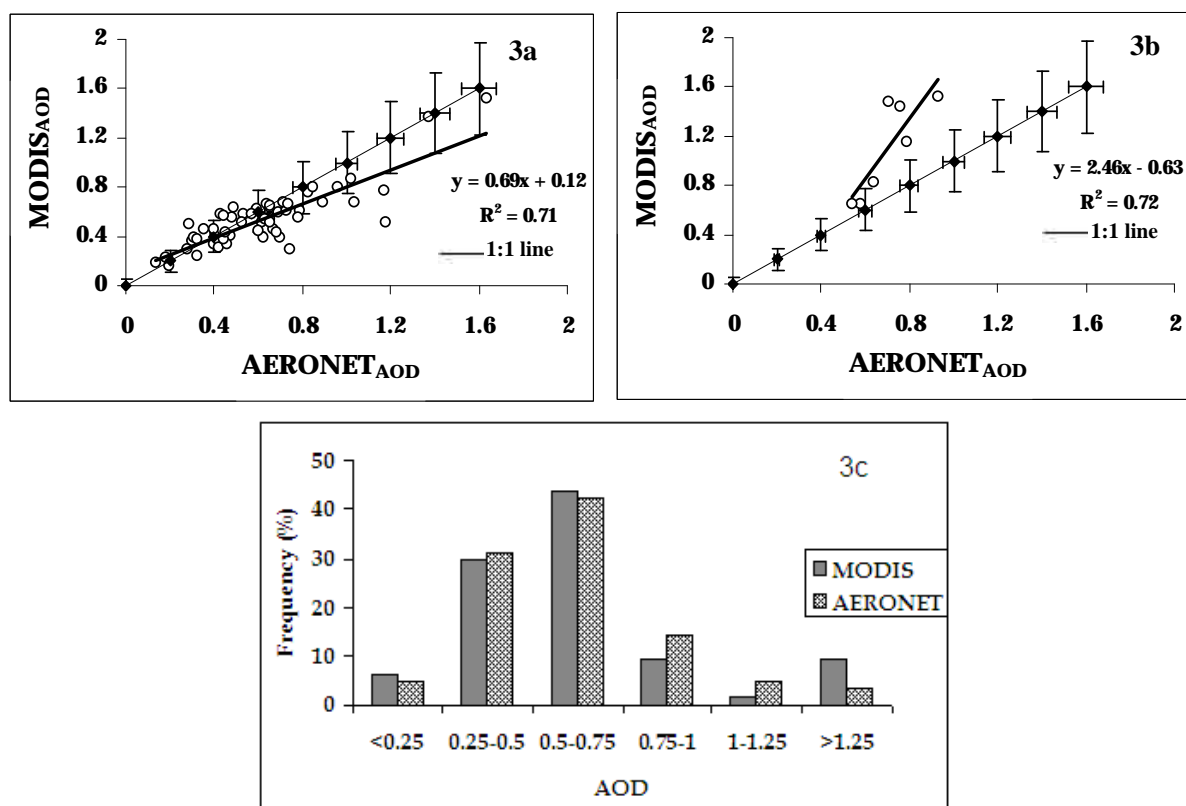
The linear and quadratic interpolation techniques have been used to derive AOD at  $0.55 \mu\text{m}$  from AERONET and the statistical parameters and correlation coefficient ( $R^2$ ) are compared. The correlation coefficients obtained from both the interpolation techniques for the month of January 2004 are shown in Table 1. The  $R^2$  values for the 2nd degree interpolation are found to be better than that of the linear interpolation, so the 2nd degree interpolation is chosen to calculate the AOD value at  $0.55 \mu\text{m}$ , from available wavelengths. To determine  $\tau_{aAERONET}$  value at the time of the overpass of MODIS over Kanpur, two points have been selected within  $\pm 15$  min of the MODIS overpass time ( $T_m$ ) and used to interpolate the value at  $T_m$ . The  $\tau_{aAERONET}$  and  $\tau_{aMODIS}$  values are merged to form a common data set for further analysis. In 2004, we have found 19 data of Terra and 46 data of Aqua matching AERONET in the specified time-space window. Using this merged data set,  $\tau_{aMODIS}$  and  $\tau_{aAERONET}$  have been compared and statistical parameters have been studied.

#### 5 Results and discussion

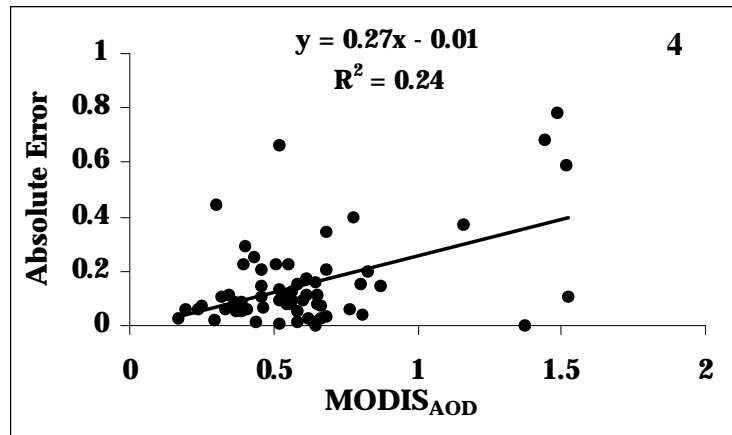
Figure 2 shows the monthly averaged AOD values at  $0.55 \mu\text{m}$  wavelength retrieved from MODIS and AERONET over Kanpur during 2004, with the number of days considered for each month (days are mentioned above the MODIS-derived AOD bar plots). AOD is found to show strong seasonal variations with maximum value ( $\tau_{aMODIS} > 1$  and  $\tau_{aAERONET} > 0.75$ ) during the summer months.  $\tau_{aMODIS}$  has been matched up with the corresponding value of



**Fig. 2.** Monthly averaged AOD at 0.55  $\mu\text{m}$  wavelength over Kanpur during the year 2004 retrieved from MODIS and AERONET. The error bars represent the standard deviation of AOD for that month. Numbers above the histogram of MODIS derived AOD represent the number of data points for the respective month.



**Fig. 3.** Scatter plot between AOD derived from MODIS and AERONET in 2004 during (a) non-dust loading period and (b) dust-loading period and (c) frequency distribution of AOD derived from AERONET and MODIS. The error bars in Figs. 3a and b indicate the range of MODIS expected accuracy ( $\pm 0.05 \pm 0.2\tau_a$ ) from the 1:1 line (along Y-axis) and the uncertainty of AERONET measurements (along X-axis).



**Fig. 4.** Scatter plot of the absolute error in  $\tau_{aMODIS}$  retrieval vs  $\tau_{aMODIS}$  over Kanpur.

$\tau_{aAERONET}$  and statistically processed within an optimum space-time window from which a scatter diagram of  $\tau_{aMODIS}$  vs.  $\tau_{aAERONET}$  has been produced during non-dust loading (January–March and September–December) and dust-loading (April–July) periods (Figs. 3a and b). Linear regression analysis was performed between the MODIS-retrieved AOD values and AERONET observations (Figs. 3a and b) in the form:

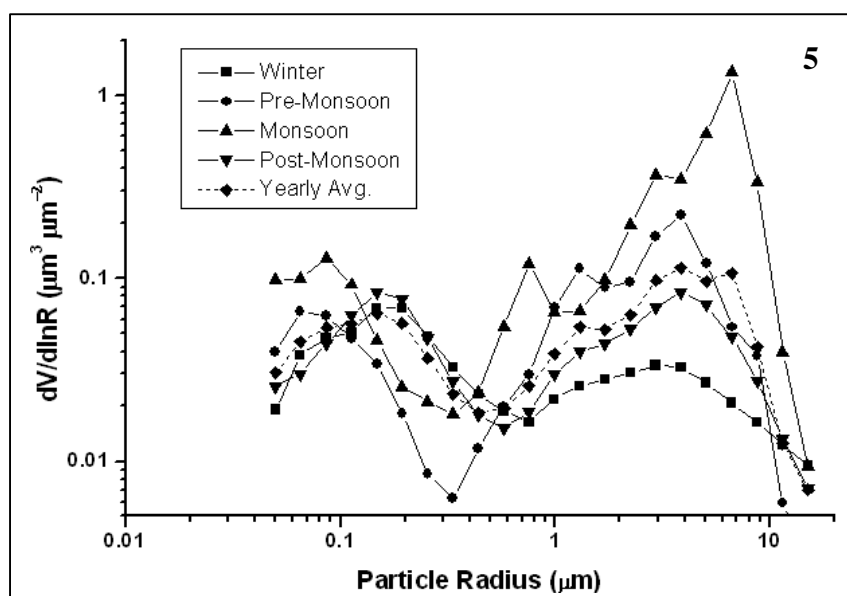
$$\tau_{aMODIS} = A + B * \tau_{aAERONET}. \quad (2)$$

Retrieval algorithm performance is validated from the resulting statistical parameters of the linear regression: A (intercept), B (slope) and  $R^2$  (square of correlation coefficient). Here non zero intercepts ( $A=+0.12$  and  $-0.63$  during non-dust and dust loading periods, respectively) show that the retrieval algorithm is biased at low AOD values, which may be associated with a sensor calibration error or an improper assumption about ground surface reflection (Zhao et al., 2002); in addition, large errors in surface reflectance lead to large intercepts (Chu et al., 2002). A slope that is different from unity indicates that there may be some inconsistency between aerosol microphysical and optical properties used in the retrieval algorithm and that in the real situation (Zhao et al., 2002). Slope lower than unity ( $\sim 0.69$ ) during the non-dust loading period (Fig. 3a) indicates an underestimation of AOD by MODIS with respect to AERONET retrieval, whereas a very high slope ( $\sim 2.46$ ) during the dust loading period (Fig. 3b) indicates an overestimation of AOD by MODIS with respect to AERONET retrieval. The effect of the combination of slope and the intercepts on the correlation of MODIS and AERONET derived AOD in the scatter plots (Figs. 3a and b) is better represented in the frequency distributions (Fig. 3c). The histograms of the frequencies in the observed range of AOD have been compared between MODIS and AERONET retrievals for all the data points. The histograms are well matched (maximum difference of 2%) for  $AOD < 0.75$ , whereas  $\tau_{aAERONET}$  is found to be higher for AOD in the range of  $0.75$ – $1.25$  compared to  $\tau_{aMODIS}$

(difference of  $\sim 4\%$ ). However, for  $AOD > 1.25$ , the difference is found to be maximum (6%).

From our analysis, it is seen that the absolute error (magnitude of error without considering the sign of error) is higher for higher AOD (Fig. 4), whereas the error in retrieving AOD from MODIS ( $\Delta\tau_a$ ) is calculated as  $\tau_{aMODIS} - \tau_{aAERONET}$  with respect to AERONET retrieval. The absolute error in retrieval of  $\tau_{aMODIS}$  shows a linear relationship with the  $\tau_{aMODIS}$ , although the correlation is poor (0.24). The error in the intercept ( $\sim -0.01$ ) and the slope ( $\sim 0.27$ ) is found to be about 25% in the retrieval of MODIS AOD. This is crucial in terms of quantification of the difference of MODIS AOD products with the ground-based measurements over Kanpur which is representative of the Ganga Basin.

The absolute difference between  $\tau_{aMODIS}$  and  $\tau_{aAERONET}$  is found to be less than 0.2 during the other months, whereas during May–July (prime time for the dust loading), the difference is abnormally high ( $> 0.35$ ). Over Kanpur,  $\tau_{aAERONET}$  is found to be the highest during summer months (Dey et al., 2004; Singh et al., 2004) when the maximum absolute error in  $MODIS_{AOD}$  has been found. MODIS is found to overestimate AOD values ( $\Delta\tau_a$  is positive) during the pre-monsoon season. During the post-monsoon season,  $\tau_{aMODIS}$  and  $\tau_{aAERONET}$  are found to show a good match. Although the correlation between  $\tau_{aMODIS}$  and  $\tau_{aAERONET}$  during the non-dust loading period ( $R^2=0.72$ ) (Fig. 3a) and dust-loading period ( $R^2=0.71$ ) (Fig. 3b) are almost equal, the regression equations show an overestimation of MODIS AOD during the dust-loading period and an underestimation during the non-dust loading period with respect to AERONET. During the non-dust loading period, very few points (for  $\tau_{aAERONET} > 1$ ) are found to lie outside the accuracy limit of MODIS ( $\pm 0.05 \pm 0.2\tau_a$ ) from the 1:1 line, whereas for the dust-loading period, the points representing  $AOD > 0.8$  lie outside the accuracy range from 1:1 line. The deviation is found to be higher for higher values of AOD during the dust-loading period. Ichoku et al. (2002) have shown that the correlation between



**Fig. 5.** Aerosol volume size distribution over Kanpur retrieved by AERONET during the winter, pre-monsoon, monsoon and post-monsoon seasons and the annual average in 2004. Enhanced volume concentration at the coarse mode is evident during the pre-monsoon season, whereas the fine mode volume concentration is found to be similar to the annual average. In the other seasons, volume concentration of the coarse mode is far less compared to that in the pre-monsoon season.

**Table 2.** Optical properties in the year 2004 during the non-dust loading and dust-loading seasons over Kanpur retrieved by AERONET.

Optical property ( $0.55 \mu\text{m}$ )	Non-dust loading period (Mean $\pm$ Standard Deviation)	Dust-loading period (Mean $\pm$ Standard Deviation)
SSA	$0.88 \pm 0.03$	$0.93 \pm 0.03$
Real refractive index	$1.46 \pm 0.08$	$1.53 \pm 0.07$
Imaginary refractive index	$0.012 \pm 0.005$	$0.003 \pm 0.001$

$\text{AOD}_{\text{MODIS}}$  and  $\text{AOD}_{\text{AERONET}}$  is moderate over land ( $R^2 \sim 0.73$ ) compared to that over the ocean ( $R^2 = 0.936$ ). Not much improvement in correlation is found, when cloud-screened level 1.5 AOD data ( $R^2 = 0.74$ ) and level 1.0 unscreened AOD data ( $R^2 = 0.75$ ) of AERONET have been compared with MODIS derived AOD (not shown). The cloud-screening algorithm of the AERONET database does not set any criterion on the Ångström parameter, otherwise it would be difficult to detect unusual events (dust storms) using AERONET data (Smirnov et al., 2000).

The aerosol type considered in the MODIS algorithm for the Ganga Basin is smoke. Kanpur is a major industrial city and the aerosols are dominantly sulfates, nitrates and other industrial pollutants (Sharma et al., 2003). During the pre-monsoon and monsoon seasons, dust is the main contributor to the observed AOD over Kanpur (Dey et al., 2004). During the pre-monsoon and monsoon seasons, aerosol size distribution shows more than 50% increase in the volume concentration in the coarse mode compared to the yearly average (Fig. 5), whereas during the post-monsoon and winter seasons, fine mode aerosols are found to be dominant.

The increase in the volume concentration at the accumulation mode during the winter season is due to the hygroscopic growth of the ambient particles (Singh et al., 2004). The refractive indices (both real and imaginary parts at  $0.55 \mu\text{m}$  wavelength) of the aerosols over Kanpur retrieved by AERONET in the year 2004 during the non-dust loading and dust-loading periods are given in Table 2. High real and low imaginary parts of the refractive index during the dust-loading period prove that in this region dust particles have a significant impact on the aerosol optical properties, which may cause uncertainties in the satellite retrieval. The uncertainty in the aerosol model has a greater impact at high AOD values (Chu et al., 2002). From the MODIS airborne simulator data acquired over Brazil, during the SCAR-B (Smoke Carbon Aerosol and Radiation-Brazil) it was found that the value of single scattering albedo (SSA) is very sensitive to the retrieved AOD (Chu et al., 1998). SSA over Kanpur has been found to be strongly wavelength dependant during the winter season and vary in the range 0.75 to 0.98 throughout the year (Singh et al., 2004), which makes the correct assumption of SSA more difficult. SSA at  $0.55 \mu\text{m}$



wavelength over Kanpur is found to be  $0.88 \pm 0.03$  and  $0.93 \pm 0.03$  (5.7 % higher) during the non-dust loading and dust-loading periods, respectively (Table 2). The dust particles are non-spherical, hence the phase function due to these particles will be different from the phase functions considered for spherical particles. The SAFARI 2000 campaign during August–September 2000 in Southern Africa also shows strong dependence of uncertainty in AOD on SSA at high aerosol loading (Ichoku et al., 2003), where the discrepancy arises due to a higher SSA value (0.9) assumed for biomass burning aerosols compared to an SSA value of 0.86 measured by ground-based instruments.

During the summer months, the surface is dry because  $\rho_s$  is high which may be a cause of the overestimation of AOD. The empirical relationships,  $\rho_s^{0.47 \mu\text{m}} = 0.25 \rho_s^{2.1 \mu\text{m}}$  and  $\rho_s^{0.66 \mu\text{m}} = 0.5 \rho_s^{2.1 \mu\text{m}}$ , established from series of measurements, are used in the MODIS aerosol retrieval algorithm (Kaufman et al., 1997b,c), but this does not hold for all surface types. The ratio  $\rho_s^{0.66 \mu\text{m}} : \rho_s^{2.1 \mu\text{m}}$  varies from slightly less than  $1/2$  for dense and dark vegetation, to slightly more than  $1/2$  for situations involving vegetation mixed with bright soils (Kaufman et al., 2002b). This aberration in the  $\rho_s^{0.66 \mu\text{m}} : \rho_s^{2.1 \mu\text{m}}$  ratio can result in uncertainties in AOD values. Moreover, an error in order of magnitude of 0.006 in measuring the surface reflectance yields an error of  $\pm 0.06$  in retrieval of AOD (Kaufman et al., 1997b). The presence of the dust particles in the atmosphere reduces the transparency of the atmosphere at the  $2.1\text{-}\mu\text{m}$  wavelength. This means that the estimation of the surface reflectance is underestimated; or in other words, the atmospheric contributions are overestimated, resulting in an overestimation of AOD. During pre-monsoon and monsoon seasons the dust events over the Ganga Basin (Dey et al., 2004) are very high, when maximum discrepancy has been observed between  $\tau_{a\text{MODIS}}$  and  $\tau_{a\text{AERONET}}$ . The dust storms are seasonal and continue from April to August every year in the Ganga Basin. The regional air mass during the pre-monsoon season in northern India flows predominantly in a southwesterly direction which transports dust particles in the basin. The frequency of the intense dust events is found to be maximum during May–June which originates from the far distance Arabia peninsula and the Thar Desert (Fig. 1). These events are found to change the aerosol optical properties significantly (Dey et al., 2004). During the pre-monsoon season, even during the absence of dust events, the particle volume concentration at the coarse mode has been found to be significantly high (2–3 times) compared to the other seasons (Singh et al., 2004). The average Ångström parameter during the dust-loading season in 2004 is found to be  $0.36 \pm 0.26$  and  $1.15 \pm 0.36$  during the non-dust season, which shows the dominance of coarse particles.

The MODIS algorithm considers the aerosol type to be smoke over Kanpur; the SSA and the refractive indices measured by AERONET during the post-monsoon and winter seasons are found to give good comparison. The main difference in the retrieval of AOD from MODIS is attributed to the

presence of dust in the atmosphere when SSA is found to be very high ( $\sim 0.93$ ), which could be due to the non-sphericity of the dust particles. Hence, the existing retrieval algorithm needs to be modified in view of the changing aerosol optical properties during the dust-loading periods.

## 6 Conclusions

Comparison between AOD derived from MODIS and AERONET over the Ganga Basin shows good comparison (average absolute difference is  $0.12 \pm 0.11$ ) during the post-monsoon and winter seasons (September–March) when dust loading is not present. During the pre-monsoon, the region suffers from dust loading due to the southwesterly winds; the average absolute difference between  $\tau_{a\text{MODIS}}$  and  $\tau_{a\text{AERONET}}$  is found to be quite high ( $0.4 \pm 0.2$ ) with the absolute error of  $\tau_{a\text{MODIS}}$  about  $\sim 25\%$  of the absolute  $\tau_{a\text{MODIS}}$  values. The difference in model and the real value of SSA, and the real and imaginary parts of the refractive indices due to the dominance of the non-spherical dust particles, is likely to be the main reason for the observed discrepancy. Our analysis shows the need for modification of the existing MODIS algorithm over the Ganga Basin, especially during the dust loading period.

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## References

- Andreae, M. O.: Climatic effects of changing atmospheric aerosol levels, in: *World Survey of Climatology*, edited by: Henderson-Sellers, A., , Vol. 16, *Future Climates of the World*. Elsevier, Amsterdam, 341–392, 1995.
- Boucher, O. and Tanré, D.: Estimation of the aerosol perturbation to the Earth's radiative budget over oceans using POLDER satellite aerosol retrievals, *Geophys. Res. Lett.*, 27(8), 1103–1106, 2000.
- Boucher, O. and Haywood, J.: On summing the components of radiative forcing of climate change, *Clim. Dyn.*, 18, 297–302, 2001.
- Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley Jr., J. A., Hansen, J. E., and Hofmann, D. J.: Climate forcing by anthropogenic aerosol, *Science*, 255, 423–430, 1992.
- Chu, D. A., Kaufman, Y. J., Remer, L. A., and Holben, B. N.: Remote sensing of smoke from MODIS airborne simulator during the SCAR-B experiment, *J. Geophys. Res.*, 103, 31 979–31 987, 1998.
- Chu, D. A., Kaufman, Y. J., Ichoku, C., Remer, L. A., Tanré, D., and Holben, B. N.: Validation of MODIS aerosol optical depth retrieval over land, *Geophys. Res. Lett.*, 29(12), MOD2, 1–4, 2002.
- Deuzé J. L., Goloub, P., Herman, M., Marchand, A., Perry, G., Susana, S., and Tanré, D.: Estimate of the aerosol properties over

- the ocean with POLDER on ADEOS-1, *J. Geophys. Res.*, 105 (D12), 15 32–15 346, 2000.
- Dey, S., Tripathi, S. N., Singh, R. P., and Holben, B. N.: Influence of dust storms on aerosol optical properties over the Indo-Gangetic basin, *J. Geophys. Res.*, 109, doi:10.1029/2004JD004924, 2004.
- Goloub, P., Deuze, J. L., Herman, M., Tanré, D., Chiapello, I., Roger, B., and Singh, R. P.: Aerosol remote sensing over land using the spaceborne polarimeter POLDER, in: *Current problems in Atmospheric Radiation*, edited by: Smith, W. L. and Timofeyev, Yu. M., A. Deepak Publishing, Hampton, Virginia, 113–116, 2001.
- Gonzalez L., and Deroo, C.: HDFLook/HDFLook MODIS Handbook, <http://www-loa.univ-lille1.fr/Hdflook/E-HDF.html>, 2003.
- Hansen, J., Sato, M., and Ruedy, R.: Radiative forcing and climate response, *J. Geophys. Res.*, 102, 6831–6864, 1997.
- Haywood, J. and Boucher, O.: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: a review, *Rev. Geophys.*, 38(4), 513–543, 2000.
- Herman, J. R., Bhartia, P. K., Torres, O., Hsu, C., Seftor, C., and Celarier, E.: Global distribution of UV-absorbing aerosol from Nimbus-7/TOMS data, *J. Geophys. Res.*, 102, 16 911–16 922, 1997.
- Holben, B. N., Setzer, A., Eck, T. F., Pereira, A., and Slutsker, I.: Effect of dry-season biomass burning on Amazon basin aerosol concentrations and optical properties, 1992–1994, *J. Geophys. Res.*, 101(D14), 19 465–19 482, 1996.
- Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A.: AERONET – A federated instrument network and data archive for aerosol characterization, *Remote Sensing of Environment*, 66, 1–16, 1998.
- Hsu, N. C., Herman, J. R., Bhartia, P. K., Seftor, C. J., Torres, O., Thompson, A. M., Gleason, J. F., Eck, T. F., and Holben, B. N.: Detection of biomass burning smoke from TOMS measurements, *Geophys. Res. Lett.*, 23, 745–748, 1996.
- Ichoku, C., Chu, D. A., Mattoo, S., Kaufman, Y. J., Remer, L. A., Tanré, D., Slutsker, I., and Holben, B. N.: A spatio-temporal approach for global validation and analysis of MODIS aerosol products, *Geophys. Res. Lett.*, 29(12), Art. No. 1616, 1–4, 2002.
- Ichoku, C., Remer, L. A., Kaufman, Y. J., Levy, R., Chu, D. A., Tanré, D., and Holben, B. N.: MODIS observation of aerosols and estimation of aerosol radiative forcing over southern Africa during SAFARI 2000, *J. Geophys. Res.*, 108(D13), doi:10.1029/2002JD002366, 2003.
- Kaufman, Y. J.: Measurements of the aerosol optical thickness and the path radiance implications on aerosol remote sensing and atmospheric corrections, *J. Geophys. Res.*, 98, 2677–2692, 1993.
- Kaufman, Y. J., Gitelson, A., Karnieli, A., Ganor, E., Fraser, R. S., Nakajima, T., Mattoo, S., and Holben, B. N.: Size distribution and scattering phase function of aerosol particles retrieved from sky brightness measurements, *J. Geophys. Res.*, 99(D5), 10 341–10 356, 1994.
- Kaufman, Y. J., Tanré, D., Gordon, H. R., Nakajima, T., Lenoble, J., Frouin, R., Grassl, H., Herman, B. M., King, M. D., and Teillet, P. M.: Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect, *J. Geophys. Res.*, 102, 16 815–16 830, 1997a.
- Kaufman, Y. J., Tanré, D., Remer, L. A., Vermote, E. F., Chu, A., and Holben, B. N.: Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer, *J. Geophys. Res.*, 102, 17 051–17 068, 1997b.
- Kaufman, Y. J., Wald, A. E., Remer, L. A., Gao, B.-C., Li, R.-R., and Flynn, L.: The MODIS 2.1- $\mu\text{m}$  channel- correlation with visible reflectance for use in remote sensing of aerosol, *IEEE Trans. Geosci. Rem. Sens.*, 35(5), 1286–1298, 1997c.
- Kaufman, Y. J., Tanré, D., and Boucher, O.: A satellite view of aerosols in climate system, *Nature*, 419, 215–223, 2002a.
- Kaufman, Y. J., Gobron, N., Pinty, B., Widowski, J., and Verstraete, M. M.: Relationship between surface reflectance in the visible and mid-IR used in MODIS aerosol algorithm– theory, *Geophys. Res. Lett.*, 29(23), doi:10.1029/2001GL014492, 2002b.
- King, M. D., Kaufman, Y. J., Tanré, D., and Nakajima, T.: Remote Sensing of Tropospheric Aerosols from Space: Past, Present, and Future, *Bull. Am. Meteorol. Soc.*, 80, 2229–2259, 1999.
- King, M. D., Menzel, W. P., Kaufman, Y. J., Tanré, D., Gao, B. C., Platnick, S., Ackerman, S. A., Remer, L. A., Pincus, R., and Hubanks, P. A.: Cloud and Aerosol Properties, Precipitable Water, and Profiles of Temperature and Humidity from MODIS, *IEEE Trans. Geosci. Rem. Sens.*, 41, 442–458, 2003.
- Krishna Moorthy, K., Niranjana, K., Narasimhamurthy, B., Agashe, V. V., and Krishna Murthy, B. V.: ISRO-GBP Scientific Report 03-99, Space Physics Laboratory, Vikram Sarabhai Space Center, Trivendrum, 1999.
- Penner, J. E., Dickinson, R. E., and O'Neill, C. A.: Effects of aerosols from biomass burning on the global radiation budget, *Science*, 256, 1432–1434, 1992.
- Remer, L. A., Tanré, D., Kaufman, Y. J., Ichoku, C., Mattoo, S., Levy, R., Chu, D. A., Holben, B. N., Dubovik, O., Smirnov, A., Martins, J. V., Li, R. R., and Ahmad, Z.: Validation of MODIS aerosol retrieval over ocean, *Geophys. Res. Lett.*, 29, doi:10.1029/2001GL013204, 2002.
- Satheesh, S. K. and Ramanathan, V.: Large differences in tropical aerosol forcing at the top of the atmosphere and Earth's surface, *Nature*, 405, 60–63, 2000.
- Sharma, M., Kiran, Y. N. V. M., and Shandilya, K. K.: Investigations into formation of atmospheric sulfate under high  $\text{PM}_{10}$  concentration, *Atmos. Environ.*, 37, 2005–2013, 2003.
- Singh, R. P., Dey, S., Tripathi, S. N., Tare, V., and Holben, B. N.: Variability of aerosol parameters over Kanpur city, northern India, *J. Geophys. Res.*, doi:10.1029/2004JD004966, 2004.
- Smirnov, A., Holben, B. N., Eck, T. F., Dubovik, O., and Slutsker, I.: Cloud-screening and quality control algorithms for the AERONET database, *Remote Sensing of Environment*, 73, 337–349, 2000.
- Tanré, D., Kaufman, Y. J., Herman, M., and Mattoo, S.: Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances, *J. Geophys. Res.*, 102, 16 971–16 988, 1997.
- Tegen, I., Lacis, A. A., and Fung, I.: The influence on climate forcing of mineral aerosols from disturbed soils, *Nature*, 380, 419–422, 1996.
- Vinod, V., Babu, S. S., Satheesh, S. K., Moorthy, K. K., and Kaufman, Y. J.: Radiative forcing by aerosols over the Bay of Bengal region derived from shipborne, island-based and satellite (Moderate Imaging Spectroradiometer) observations, *J. Geophys. Res.*, 109, doi:10.1029/2003JD004329, 2004.
- Zhao, T. X.-P., Stowe, L. L., Smirnov, A., Corsby, D., Sapper, J., and McClain, C. R.: Development of a global validation package for satellite oceanic aerosol optical thickness retrieval based on AERONET observations and its application to NOAA/NESDIS operational aerosol retrievals, *J. Atmos. Sci.*, 59, 294–312, 2002.